Sediment Particle Characterization for Acoustic Applications: Coarse Content, Size and Shape Distributions in a Shelly Sand/Mud Environment

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***Abstract*— Coarse particles in the sediment samples collected during the sediment acoustics experiment (SAX04) in shallow water off Fort Walton Beach, Florida, were analyzed in the 0 to –5 phi sieve size range, at quarter-phi intervals. Conventional size frequency histograms were determined and compared with results obtained by others at the SAX04 site. In addition, the coarse content was analyzed separately for the two populations, quartz (sand) and carbonate (shell) particles, using independent measurements of total weight and number of particles in each size interval. With this approach, four size distributions were measured, instead of a single one as in traditional sieving techniques. This analysis resulted in a modified technique, which can be used to improve geoacoustic characterization of the sediment. A particle shape factor was introduced for a simple quantification of the difference between the sieve size and true size (equivalent spherical particle diameter). It is shown that shells and shell fragments have a shape factor significantly different from that for sand particles. The size distributions for the two populations are also shown to be different. Empirical relationships are established between the shape factor, sieve size, and true size, for both carbonate and quartz particle populations. Using these relationships, the true size distributions, required in acoustic applications, were determined by correction of traditional sieve size distributions. These corrections are based on replacement of the "spherical shape" assumption used in traditional techniques by the "typical shape" assumption, using the shape factors measured for the two populations. Finally, to test the corrected distributions, they were compared with those obtained using a new approach allowing estimation of the true size distributions without particle sieving and/or separating into size intervals (bins). The true size distributions obtained in this work will provide input parameters and ground truth for model/data comparisons using SAX04 acoustic backscattering measurements.**

***Index Terms*—Coarse sand, gravel, shell fragments, sieve size, true size (equivalent diameter), particle size and shape distributions.**

I. INTRODUCTION

Marine sediment is comprised of particles having different size, shape, mineral composition, density, elasticity, and other properties. The particle size distribution is one of the major characteristics which determine geotechnical, physical, and geoacoustic properties of the sediment. The mean grain size has a significant statistical correlation with, and, therefore, a capability to predict, such fundamental physical and acoustic parameters of the sediment as the bulk density, porosity, sound speed and attenuation [1]. However, attempts to find empirical relationships with other acoustic properties of the sediment have had much less success. For example the bottom backscattering strength, reported in a number of comprehensive experimental studies in a wide 10- to 500-kHz frequency range, has shown little correlation with the mean size of sediment particles: see, e.g., [1,2], and references therein. Another common approach is to classify sediments in terms of their mud, sand, and gravel content, expressed as weight % (cumulative weight percentage), resulting in so-called Folk classes, e.g., sandy mud, gravelly sand, etc. However, these parameters, usually presented in existing data bases as well as the mean size, also may be insufficient for acoustic characterization of the sediment. For example, sandy sediments with 1% or less gravel content are usually considered and documented as belonging to just the "sand" Folk class [1]. However, even such a small gravel content can significantly change the scattering characteristics of the seafloor [3,4], and, therefore, should be taken into account for sediment acoustic characterization.

Manuscript received March 31, 2009. This work was supported by the U.S. Office of Naval Research.
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Goff et al. [3] came to a conclusion that coarse particle contributions, commonly significant in shallow water sediments, should be analyzed separately from fine (mud or silt/clay) and medium (sand) fractions, and in terms somewhat different from Folk classes. It was noticed that the coarse content may increase attenuation through scattering. Earlier experimental work [2] also provides examples where variations in geoacoustic measurements and coarse material (such as shell hash) are correlated. A strong positive correlation was established between the coarse content and the measured bottom backscattering strength at high frequencies: 65 kHz [3], 100 kHz [5,6], 100 kHz and 410 kHz [7]. Physics-based theoretical models of bottom scattering capable of explaining this effect also have been developed [4,8-10]. The modeling has showed however that predicting the bottom scattering strength in such a wide frequency range requires a more detailed description of the coarse size distribution, rather than a single number characterizing the total coarse content. Therefore, a more detailed study of the coarse sediment fraction is important for an adequate geoacoustic characterization of the seafloor.

The size itself can be defined differently when different measurement techniques are used [11-14], emphasizing different aspects of sediment particles, which are commonly non-spherical. It is therefore not always appropriate to use directly results of such measurement as inputs in models, if they define the size differently. First, relationships between these different measures of particle size should be established. For example, sieve analysis operationally defines the particle size from the dimension of the smallest square mesh which can be passed through by this particle. Models of acoustic scattering from sediment inclusions or coarse particles require inputs in the form of the number-size distribution, or the particle number per unit sediment volume per unit size interval, with the size defined as the equivalent spherical diameter [4,9], which is also called the particle "true size" or the "true nominal diameter" [12]. In traditional weighing-sieving techniques, widely used for sediment particle size analysis, the number-size distribution is commonly estimated using the assumption that the particles are nearly spherical [1], and consequently the particle true size is nearly equal to their sieve size. Commonly, however, the sediment particles are non-spherical, and, therefore, a more accurate relationship between the particle sieve size and true size (instead of their simple equality for spherical particles) is required. Their difference, from an acoustic viewpoint, is the only measure of the non-spherical particle shape relevant to this specific application (modeling of acoustic scattering). Obtaining empirical relationships, describing this difference and allowing a corresponding size-correction for the sediment non-spherical particles, is one of the goals of this work.

In this paper, we focus on analysis of the sediment particles corresponding to a "coarse tail" of the size distribution, i.e., coarse particles with size significantly larger than the mean grain size of the sediment. Information about this part of the size distribution is quite sparse in comparison with that for the central part. One reason is that coarse particles usually have an insignificant effect on the mean grain size and other traditional grain size statistics. Another reason is that obtaining such information requires larger sediment samples. This was taken into account in planning acquisition and analysis of the sediment coarse particles collected during a major sediment acoustics experiment (SAX04). This experiment was accompanied by extensive environmental measurements to evaluate the acoustic parameters of the sediments, including the density, sound speed and attenuation, their spatial variations in the sediment (volume heterogeneity), as well as the sediment interface roughness [15-21]. The main goal of such measurements was to provide environmental inputs to various models of sound-bottom interaction, and particularly to SAX04 bottom scattering models and model/data comparisons in a wide range of frequencies: 20 kHz to 500 kHz [22]. To evaluate the role of the sediment discrete scatterers in this frequency range, the particle size distribution has to be determined for sizes larger than about 1 mm [4], including very coarse sand-, gravel-, and pebble-sized particles. Obtaining this size distribution for the SAX04 sediment coarse fractions, its analysis, and an adequate parameterization, are the main goals of this work.

The paper is organized as follows. Section II outlines methods used for sediment particle characterization, sample collection and processing. Assumptions used in traditional weighing-sieving techniques are discussed to show what additional measurements are required if these assumptions fail. In Section III, available size distributions measured at the SAX04 site using traditional techniques are summarized and compared. New results obtained using other approaches and additional measurements are presented. In particular, size distributions are obtained, based on separate analysis of the two segregated populations (or phases), shell (carbonate) and sand (quartz) particles, comprising the SAX04 sediment. In Section IV, the shape factor is introduced and relationships between the particle true size (equivalent diameter) and sieve size are established. The true size and shape factor as functions of the sieve size are approximated by empirical power law relationships. In Section V, the effect of the non-spherical shape of the particles on the size distributions is discussed and corresponding corrections, based on empirical relationships obtained here, are proposed to provide required true size distributions. Also, another novel method for direct estimating the true size distribution without particle sieving is proposed. Section VI gives a summary and conclusions. In Appendix A, empirical relationships used in this paper for particle characterization are presented. Appendix B provides useful phase relationships for the quartz/carbonate mixture considered in this paper.

II. METHODS

A. SAX04 environment and sediment sample collection

The SAX04 acoustic experiments and supporting environmental measurements took place in shallow water about 1 km off shore near Fort Walton Beach, Florida, in September – November 2004. For the research described in this paper, thirteen sediment samples were collected and processed, with a total volume of 189 liters. They were collected in several locations,

chosen in proximity to the three major SAX04 acoustic measurement systems, the Benthic Acoustic Measurement System (BAMS), the Synthetic Aperture Sonar (SAS), and the Sediment Transmission Measurement System (STMS). The STMS was located about 60 meters westward from the SAS, and the BAMS location was about 200 meters eastward from the SAS. The spatial layout and locations of these systems are described in [22,23] in more detail. The three sites, and samples collected at these sites, are referred to below as BAMS, SAS, and STMS sites and samples respectively.

It is important to mention that not only the total volume of the sediment samples, but also the cross section of each sample should be chosen large enough to allow unbiased collection of the larger, less numerous particles. The dimensions of the samples collected for this work were chosen to allow unbiased evaluation of the gravel- and pebble-sized particles, which can be important for acoustical scattering at frequencies as low as 20 kHz used in SAX04 experiments [4]. Ten cylindrical samples of 20 cm diameter, the BAMS and SAS samples, with total volume about 19 liters were collected by divers on 5 October 2004 and contained the sediment of the upper 6 cm. The five BAMS samples were collected along a westward line starting about 10 meters from the BAMS tower base and then with spacing 1, 2, 3 and 4 meters between adjacent samples. Five SAS samples were collected along a northeastward line starting about 1 meter from the east end of the SAS rail with the same spacing (1, 2, 3 and 4 meters). The three STMS samples were obtained on 6 October 2004 from a larger sediment volume (about 160 liters). This sediment was excavated from the upper 0 to 18 cm during deployment of the STMS apparatus and divided into three layers 6 cm each.

It should be noticed that the SAX04 sediment had rather complicated spatial distribution and structure, resulted from strong weather events (Hurricane Ivan and Tropical Storm Mathew) [19,21]. In particular, the sediment textural content at the three sites was somewhat different. According to diver's reports [24,25], the sediment at the STMS site was comprised predominantly of clean sand with very little (if any) mud, while the sediment at the SAS and BAMS sites was much less clean, with a noticeable mud content, most pronounced for the BAMS locations. However, in available documents, in spite of quite non-uniform spatial distribution of mud, it was characterized, as usual, by a single value, the average mud content, obtained by averaging over all numerous sediment samples collected at the SAX04 site. The average mud content in the SAX04 sediment was about 8.5% by volume [19]. Gravel (mostly shell) content was less than 1% by volume. Such small contributions, from a geotechnical viewpoint, can be considered insignificant and may be ignored. In ternary Folk diagrams based on gravel-sand-mud ratio, see [1, p. 88], the SAX04 sediment is characterized as just "sand".

More information about SAX04 sediment properties can be provided by parameters of the grain size statistics (mean size, sorting, skewness, and kurtosis), which traditionally are considered as the main descriptors of the sediment type as well as related "word-based" characteristics (e.g., fine, medium, or coarse sand, well or moderately sorted). Along with the sediment textural parameters (defined by Folk-class), they are commonly well documented in numerous existing data bases. Analysis of the grain size statistics clarifies that the SAX04 sediment is a moderately well sorted medium sand, with mean grain size 0.36 mm [19]. However, such clarification adds very little to characterization of acoustic scattering properties of the sediment. From an acoustic viewpoint, the SAX04 environment can be more adequately characterized as a sand/mud [22], a shelly sand, or a shelly sand/mud mixture [4], with spatially varying mud and shell components, because even such small shell and mud content and their spatial distribution can be important inputs in models of bottom scattering and model/data comparisons.

B. Sieving techniques and size frequency histograms

All our sediment samples were pre-sieved before analysis. The remaining sediment coarse particles comprised only a small volume proportion of the sediment (about 1%), simplifying the following analysis and related procedures (conservation, transportation, etc). The BAMS and SAS samples were pre-sieved after being delivered onboard, and only particles with sieve size 1 mm and larger were left in the samples. The STMS sediment was placed in bags with 1.6 mm mesh and pre-sieved by shaking underwater. Hence, all mud, medium sand, and most of the coarse sand fraction, were washed out. The particle size distributions were determined using a set of 20 standard sieves in the 1.0 mm to 32 mm sieve size range, or in the 0 to –5 phi range, at quarter-phi intervals (bins). There were no particles found with larger size. Therefore, the particle data base used for analysis in this paper includes only the very coarse sand-, gravel-, and pebble-sized particles. The collected particles are significantly larger than the mean grain size, and constitute the coarse "tail" of the size distribution.

The conventional sieving-weighing techniques [1] define the weight-size distribution histogram, most commonly used in the literature, as follows

$$\Psi_W = \Delta W / W_s , \tag{1}$$

where ΔW is the dry weight of all particles in the sieve-size interval $[d, d + \Delta d]$, and W_s is the total dry weight of all solid particles of the entire (not pre-sieved) sediment sample. For pre-sieved sediment samples, the total dry weight can be estimated from the relationship

$$W_s = \rho_s (1 - P) V , \tag{2}$$

if the total volume of the wet (water saturated) sediment sample, V, the sediment porosity, P, and the average density of all solid particles in the entire sample, ρ_s, are known.

Another traditionally measured quantity is the frequency size cumulative function, which is defined as a function of size, from summation of the histogram over particles larger than this size. Therefore, it integrates information about the coarse tail of the size distribution, which, in this paper, is the primary interest. The frequency size cumulative function represents a cumulative weight percentage of coarse particles, or the coarse content of the sediment, as function of its nominal "coarse" size. This is important, because the "coarse content" can be defined differently, depending on the sediment type, related techniques, acoustic effects, etc. For example, it can include all medium sand-sized particles of predominantly fine sand or mud [1], or only pebble-sized particles (larger than 4 mm), as in [3], which were found to be responsible for certain acoustic effects. In this paper, all particles with the sieve size larger than 1 mm, including very coarse sand-, gravel- and pebble-sized particles, are included in the sediment coarse content. In predominantly medium sand sediment at the SAX04 site, all these particles are significantly larger than the mean grain size, and therefore correspond to the coarse tail of the particle size distribution. Also, they all have a certain effect on scattering properties of the SAX04 sediment in the required frequency range, 20 kHz to 500 kHz [4].

C. Outline of required additional measurements

It should be noticed that acoustic characterization of the sediment particles, for example, description of their scattering characteristics, requires inputs for the particle size in a form different from given by traditional weight-size frequency distributions. The inputs should be presented as histograms or distributions, showing the number of particles in given true size intervals per unit volume of the sediment. The required size distributions can be obtained using several assumptions. The traditional approach is to assume that all particles are nearly spherical. In this case, the sieve size is nearly equal to the true size, as it provides a sufficiently accurate estimate for the particle volume. It is commonly assumed also that all particles have the same density. Then the number of particles in each size interval can be estimated from their total weight and the required number-size distribution can be obtained from the particle weight-size distribution as follows:

$$\Psi_{Ns} = \Psi_W (1-P)/v_s \,, \tag{3}$$

$$v_s(d) = \pi d^3/6 \,, \tag{4}$$

where v_s is the volume of a spherical particle with diameter d. However, neither of these two mentioned assumptions were satisfied in the case of the SAX04 sediment samples, comprised of particles with different density and shape. Generally, the coarse particles comprised a mixture of two visually distinct populations, quartz (sand/gravel) and calcium carbonate particles (mostly broken shells). They have different shapes, especially non-spherical for coarse shell particles, and different acoustic parameters (constituent density and elastic moduli) resulting in differences in their individual scattering characteristics. In this case, scattering models require separate inputs for these two types of particles [4].

Therefore, some modifications of technique were made and additional measurements were performed to provide an appropriate description of the sediment coarse particles for acoustic scattering models. One modification to traditional techniques was that the two populations were segregated from each other and analyzed separately. The bins of the pebble size range (4 mm and larger) contained only carbonate particles. The quarter-phi bins of the 0 to –2 phi range (1 to 4 mm), corresponding to very coarse sand- and gravel-sized particles, contained a mixture of the two populations. They were segregated from each other, and the total weight of particles in each of the two populations was measured in each of the sieve-size bins. A second modification was to take into account that coarse particles were significantly non-spherical, especially the shells. To do this, the following additional measurements were made. First, the particle number in each sieve size bin was determined for each of the two populations. As the particle density in each population is defined, the average volume of particles in each size bin was estimated from their weight without assumptions on their shape. Then the ratio of the average particle volume to the volume of a sphere with the same sieve size was determined in each size bin as a simple measure for quantification of the "typical shape" of particles in each population, defined in this paper as the "shape factor". The particle volume also defines its true size (equivalent diameter). Therefore, measuring the shape factor also allowed determination of the relationship between the sieve size and true size of the particle. Then the required true size distributions were found using the corresponding corrections of the measured sieve size distributions. Generally, these corrections are based on replacement of the "spherical shape" assumption by the "typical shape" assumption, using the two different shape factors measured for the two populations, carbonate and quartz particles. Therefore, to provide the true size distributions for the SAX04 sediment coarse particles, four different size distributions were to be measured, that is two distributions, volume- and number- based, for each of the two populations. This approach was used in this paper and the results are described in more detail in the next sections.

D. Other (non-sieving) techniques

There are many other ways of determining the size and shape of the sediment particles. It is understood that 3-D non-spherical particles generally may require three or more parameters to characterize their size and shape [14]. Numerous methods for such characterization are based on processing of particle images. Many of them are based on rather time consuming grain-by-grain analysis of particle projected area for particles placed on a gridded screen [11,14]. Also based on the image analysis, but without extracting individual grains from the sediment samples, are the methods using X-radiography and computed tomography (CT):

see, for example, [1, Ch. 7], [10,18,26]. These methods cause lesser disturbance to the sediment structure than the usual sieving process, but also have some disadvantages, outlined as follows.

First, CT methods do not provide direct measurements of the particle size, but rather 2D-images of contours or cross-sections shifted with respect to the particle centers. Correspondingly, this allows estimation of size distributions for these 2D-images, which, however, are different from the desired actual size distributions. To make corresponding corrections, even in the simpler case of spherical particles, some additional and rather complicated numerical procedures are needed [10,27]. Second, X-radiography and CT methods are based on distinguishing particles by density contrast, and therefore can be less efficient in the case where particles with very different shapes have relatively small difference in density, as for the carbonate (shells) and quartz (sand) particles considered here. In the only known (to the author of this paper) example presenting final results on the sediment particle size distribution measured by this technique [10], these two types of particles were not distinguished. And last, but most important in practice, this method is much more complicated and expensive than sieving.

It should be noted also that obtaining the tails of the particle size distribution from inversion of 2-D images requires numerically much more stable algorithms than for estimating parameters of the central part of the size distribution. This stability is known to be the main problem of currently used inversion techniques [27]. Therefore, the practical applicability of X-radiography and CT methods in determining the particle size distribution in granular sediments (especially the size distribution tails) has yet to be tested. Such tests could be provided by comparison of size distributions resulting from these procedures with actual size distributions measured directly, using, for example, traditional sieving techniques, or modified as described in this paper, if needed. This has not been done yet and could be an interesting task for future work.

In this paper another simple and practical approach, not based on particle sieving, is proposed for an independent measurement of the particle true size distribution. This method is based on a grain-by-grain analysis of a relatively small number of the largest particles and can be practically useful for estimating the coarse tails of the true size distribution. This approach was used in this paper to provide a comparison of different techniques, sieving- and non-sieving based. The results are presented and discussed in next sections. The proposed new techniques also can be used to test other methods based on non-direct estimation of the particle size distributions.

III. Size distributions

A. Size frequency histograms

In this paper, as an initial part of particle size analysis, the traditional weight-size distribution histograms were determined for all 13 pre-sieved sediment samples, using relationships (1) and (2). Typical values of the sediment porosity and solid density at the SAX04 site, $P = 0.37$ and $\rho_s = 2.65$ g/cm^3 [19], were used for calculations. The sediment volume for calculations was taken to be 1885 cm^3 for each of the five BAMS and five SAS samples, and 5.28×10^4 cm^3 for each of the three STMS samples. The histograms obtained in the three sites (BAMS, SAS, and STMS) were averaged over the corresponding number of samples, 5 for each of BAMS and SAS sites, and 3 for STMS site. Results are shown in Fig. 1(a) (by black symbols) in the form of the weight percentage, or frequency size distribution for the three sites. Fig. 1(b) shows the corresponding cumulative functions.

Fig. 1 also shows (in green) three data sets obtained at the SAX04 site by other authors. Two of these data sets [28] were obtained at the same time a few months before the SAX04 experiment, using the methods mentioned above for pre-sieved and entire samples. A relatively large volume of the sediment from the bottom surficial 5 cm layer was collected by divers and placed underwater in two 5-gallon buckets. The sediment in one of the buckets was pre-sieved using a 1.6 mm mesh, and only the remaining particles were used later to determine the coarse particle size distribution. This method is similar to that used for collection of our STMS samples. The sediment from the second bucket was saved and later processed in laboratory conditions as an entire sample, to determine another size distribution. The coarse content, however, was considered too small, and coarse particles larger than 2 mm were accumulated in one size class (with sieve-size 2 mm). At smaller sizes, this second size distribution and corresponding cumulative function have a consistent continuation (toward smaller sizes) of the first distribution, obtained for coarse particles from the pre-sieved sample. The third size distribution shown in Fig. 1 (in green) [19,29] represents results averaged over 23 cylindrical cores with 5.9 cm diameter collected during SAX04 and processed as entire samples.

Comparison of all the data presented in Fig. 1, ours and those obtained by other authors, shows two noticeable effects. First effect is seen from comparison of the two distributions measured using small and large sampling apertures (5.9 cm vs 20 cm), and confirms that the large but less numerous particles (with the size larger than 5 mm) can be missed if the cross section of each sample is not big enough for unbiased collection of these particles. The second effect is seen from comparison of our data obtained in the three locations at the SAX04 site. It shows positive correlation between the spatial variations in content of coarse particles in our pre-sieved sediment samples and the spatial variations in the mud content of the sediment reported by divers, that is greater coarse content was found in locations with greater mud content. Unfortunately, there is no other, more quantitative, assessment of such a correlation, which might be important for more adequate characterization of the SAX04 sediment for acoustic applications. This could be an interesting topic for future research in complicated environments (such as at the SAX04

site).

B. Volume-size distributions for carbonate and quartz particles

Unlike traditional techniques, the two populations, shells and sand particles, were segregated and the weight of particles belonging to each bin was measured separately for each population. Given the same density for particles in each population, relative measurements of weight and volume of grains are equivalent. The volume-size distribution histograms can be obtained as follows:

$$\Psi_v = \Delta V / V, \qquad (5)$$

where $\Delta V = \Delta W / \rho$ is the total volume of particles in each bin, and ρ is the particle density. It should be noticed that unlike traditional size frequency histograms given by (1) and (2), determining this histogram does not require knowledge of the sediment porosity and solid density, which cannot be measured if only pre-sieved samples are available. This volume-size distribution histogram, or, for brevity, V-histogram, can be also called "partial volume concentration", representing the volume fraction occupied by particles of a given population (with a given density) in a given sieve-size interval. In the following calculations, the typical values used for densities of quartz (sand) particles and calcium carbonate (shell) particles were taken to be 2.65 g/cm^3 and 2.75 g/cm^3, respectively (see, e.g., [1, p.112]). The corresponding cumulative function represents a "cumulative volume concentration" of a given population including coarse particles larger than a given size. It gives, for example, gravel content, if this given size is chosen to be 2 mm. An important property of the cumulative concentration is that, unlike the partial concentration, it is independent of the size of intervals or sieve bins, which can be different in different measurement techniques. This property will be used later in comparison with results obtained with different (sieving and non-sieving) techniques.

Fig. 2 shows the V-histograms and corresponding cumulative functions for each of the three sites, BAMS, SAS, and STMS, calculated separately for shells and sand particles. It is seen that shells have very different properties than coarse sand (mainly quartz particles). For example, the slopes of the size distributions of shells are very different than those for sand particles (being much steeper for sand). From Fig. 2(a), one can easily see that this difference in slopes results in dominance of the shell particles (by occupied volume) over quartz sand particles at all sieve sizes larger than a certain "transition size", which appears to be the same, about 2 mm, for all three locations.

Fig. 2 also demonstrates much spatial variability of the size distribution and coarse content for both quartz and carbonate particles. One can notice also their substantial increase in locations with greater mud content. It is interesting to note, however, that the ratio of the volume-size distributions of the two populations, shell and sand particles, or the volume ratio R_v, is much less dependent on mud content and is about the same for all three locations, and, therefore, is not affected by the mud content. Fig. 3(a) demonstrates this effect and shows the volume ratio as a function of the sieve size. One can see that it can be well approximated by a power-law dependence; see (A.1) in Appendix A.

For a mixture of particles with different densities, the definition (5) for the V-histogram is still valid assuming, however, that the density ρ represents the average value for the mixture of particles with given sieve size. The average density in the quartz/carbonate mixture is related with the volume ratio of the two components, R_v (see Fig. 3(a) and (B.1) in Appendix B), and also is size dependent. It is shown as a function of the sieve size in Fig. 3(b) for the three locations. The solid line shows the relation (B.1) for the average density with the power-law approximation for the volume ratio, given by (A.1) in Appendix A. This figure more clearly demonstrates the transition effect, noticed first in Fig. 2(a). Fig. 3(b) also shows that in the quartz/carbonate mixture there is a transition size, about 2 mm, and that quartz particles dominate at smaller sizes, while at sizes greater than this transition size the carbonate particle population is the dominant one. Note also that the average particle density, as well as the volume ratio, appears to be spatially independent. This can be important in a practical sense because it can provide alternative ways for estimating the volume-size distributions of the carbonate and quartz particles, based on simple phase relationships for the mixture of the two components (or phases), see (B.2) and (B.3) in Appendix B.

C. Number-based size distributions

In addition to measuring the weight of particles, their number in each bin for each of the two populations, carbonate and quartz particles, was counted as well. Corresponding number-size histograms were defined as follows:

$$\Psi_N = \Delta N / V, \qquad (6)$$

where ΔN is the total number of the particles in the sieve size interval $[d, d + \Delta d]$. Therefore, unlike traditional estimates based on the assumption that the particles are nearly spherical, see (3), the particle number-size distributions were measured independently of the weight-size histograms. It should be noted that segregation and counting of smaller and more numerous particles is a rather time consuming process. In bins with the two smallest sieve sizes, 1.0 mm and 1.18 mm, the number of particles was estimated, in each of the two bins for each sample, from analysis of a certain proportion of the particle population chosen to be large enough to keep statistical errors within 1% limits. Usually it was sufficient to count about a quarter or one

eighth (by weight) of the particles.

The number-size distribution histogram, or, for brevity, N-histogram, can be also called the “partial number concentration”, representing the number of particles of a given population per unit sediment volume in a given sieve-size interval. The corresponding cumulative function represents a “cumulative number concentration” of a given population including coarse particles larger than a given size. Fig. 4 shows the N-histograms and corresponding cumulative functions for each of the three sites, calculated separately for shells and sand particles. Fig. 4, as well as Fig. 2, demonstrates the very different properties of coarse sand and shell particles, and show a substantial increase in level of their size distributions in locations with greater mud content. However, the ratio of the size distributions of the two populations is again practically independent from the mud content. The carbonate-to-quartz number ratio, R_N , is shown in Fig. 5(a) to demonstrate this interesting independence. It is seen also that this ratio parameter can be well approximated by power law dependence, given by (A.2) in Appendix A, with the slope defined by the power exponent, not much different from that for the volume ratio parameter shown in Fig. 3(a). The “ratio of ratios”, or the R -parameter, $R = R_v / R_N$, is shown in Fig. 5(b). One can see that its typical level is about 0.4, and slightly decreases with increasing size. This behavior is approximated by a power-law dependence (shown by a solid line) given by (A.3) in Appendix A. As it will be seen later, the R -parameter also plays a role in characterization of the particle shape.

IV. Particle shape and true size

A. Shape factor

Independent measurements of the particle number, unlike traditional techniques using the spherical particle assumption to estimate this number, see (3), can be used also for quantification of the deviation of the particle shape from spherical. Indeed, the average volume of particles with given sieve size can be estimated as follows:

$$v(d) = \Delta V / \Delta N \, , \tag{7}$$

and then compared with the corresponding volume of the spherical particle v_s , see (4)-(6). The ratio

$$F(d) = v(d) / v_s(d) \tag{8}$$

can be considered as a parameter characterizing the difference of the particle shape from spherical, or as a shape factor. For spherical particles, $F = 1$. Particles with a lesser shape factor have volume smaller than the estimate based on their sieve size. These particles tend to have platy, disk-like shapes [12,14,26]. Particles with a greater shape factor, $F > 1$, have volume exceeding the spherical, and tend to have an elongated shape.

The results of measurements for the particle shape factor are shown in Fig. 6(a) for all three locations, presented as functions of the sieve size. This figure also illustrates the difference between the “typical shape” of sand and shell particles. One can notice that the ratios of their shape factors, and volume-to-number histograms, are the same, i.e.,

$$R = R_v / R_N = v_c / v_q = F_c / F_q \, . \tag{9}$$

This was taken into account to provide consistency of power-law empirical approximations for the shape factors of carbonate and quartz particles, which are given by (A.4) and (A.5) in Appendix A. It is seen that shells are especially non-spherical, with the shape factor for most of them being in the range 0.5 to 0.1, which corresponds to platy shapes. Most sand particles have shape factor in the range 1.0 to 1.3, which corresponds to much more round and slightly elongated shapes.

For a mixture of particles with different shape factors, the definition (8) gives the average shape factor, which is related to the number ratio of the two components, R_N , see (B.4) in Appendix B. The average shape factor is shown as function of the sieve size in Fig. 6(b) for the three locations. The solid line shows the approximation using (B.4) for the shape factor with empirical relations (A.2), (A.4.), and (A.5), see Appendix A. Note also that the average shape factor, as well as the number ratio, appears to be spatially independent. This can be important practically because it can provide alternative ways for estimating the number-size distributions of the two components, based on simple phase relationships in their mixture, and without the time consuming process of their segregation and counting, see (B.5) and (B.6) in Appendix B.

B. True size

The true size (equivalent diameter) of a non-spherical particle, D , or the diameter of the sphere having the same volume, as a function of the particle sieve size, can be determined from the equality

$$v_s(D) = v(d) \, . \tag{10}$$

It also can be expressed through the particle shape factor using definition (8), which can be written as a relationship

$$F = (D / d)^3 \, . \tag{11}$$

Therefore, given the shape factor as a function of the sieve size, $F(d)$, the particle true size also can be determined at any sieve

size as follows:

$$D(d) = d\,F^{1/3}(d)\,. \tag{12}$$

The results of measurements for the particle true size are shown in Fig. 7 for the three locations. Fig. 7a shows the true size separately for quartz (sand) and carbonate (shell) particles. It is seen that they are different and can be well approximated by two different power-law functions (solid curves), given by (A.6) and (A.7) in Appendix A. The equation (12) defines also the average true size of particles in the sand/shell mixture, which is shown in Fig. 7(b). The solid line corresponds to (12), where the shape factor is approximated by dependence (B.4) shown previously by solid curve in Fig. 6(b), and provides a good fit to measured data.

V. Correction for size distributions

A. *"Spherical shape" assumption-based distributions*

The number of particles can be estimated from their total volume using various assumptions on their shapes. For spherical particles it can be obtained as follows:

$$\Psi_{Ns} = \Psi_v / v_s\,, \tag{13}$$

which is similar to estimating the number of spherical particles from their total weight, see (3). Results for these estimates are shown in Fig. 8(a) for quartz and carbonate particles by circles. They were obtained from the volume-size histograms shown in Fig. 2(a) for BAMS and SAS sites and averaged over all ten samples. For comparison, the directly measured number-size histograms are shown by ∇-symbols, also averaged for these ten samples. It is seen that using the sphere assumption results in a significant underestimate of the number concentration of carbonate shells, while giving a slightly overestimated number for quartz sand particles.

Analogously, if the number of particles is known, their total volume can be estimated using the assumption of a spherical shape as follows:

$$\Psi_{vs} = v_s \Psi_N\,. \tag{14}$$

Results for these estimates are shown in Fig. 8(b) by circles. They were obtained by using number-size concentrations averaged over ten BAMS and SAS samples shown in Fig. 4a. Directly measured volume-size histograms are also shown (by ∇) for comparison. It is seen that using the sphere assumption results in a significant overestimate of the relative volume of carbonate shells, while giving a somewhat underestimated relative volume for quartz sand particles.

B. *"Typical shape" correction for size distributions*

Corrections for the number- and volume- sieve size distributions can be made by allowing a non-spherical shape of the particles. For example, empirical relationships for shape factors of carbonate and quartz particles obtained in this work can be used assuming that they describe typical shapes for particles of these two types, which is an improvement compared to the spherical shape assumption. This "typical shape" assumption results in estimating the number-size distributions of non-spherical particles as follows:

$$\Psi_N = \Psi_{Ns} / F\,. \tag{15}$$

Results for such estimates are shown in Fig. 8(a) (by triangles, Δ) and were obtained from previously shown (by circles) estimates corrected by using (15) with the shape factor of carbonate and quartz particles given by empirical relationships (A.4) and (A.5) in Appendix A. It is seen that such correction results in a good fit to the actually measured number-size histograms discussed above.

Analogously, if the number-size distribution of particles is known, their volume-size distribution can be estimated using the typical shape assumption as follows:

$$\Psi_v = \Psi_{vs} F\,. \tag{16}$$

Results for these estimates are presented in Fig. 8(b) (by Δ) and show a good fit to directly measured volume-size histograms averaged for all BAMS and SAS samples (shown by ∇). The comparisons in Fig. 8 demonstrate the potential practical use of the empirically introduced corrections for traditional techniques based on replacing the "spherical shape" assumption by the "typical shape" assumption.

Using empirical relationships between sieve size and true size of the particles, the measured sieve size distributions can be also presented as functions of true size. It should be noted that the corresponding sieve size and true size intervals can be different for non-spherical particles. This, however, does not affect the size distribution cumulative functions, which are independent of the size interval. Results for the cumulative functions for both carbonate and quartz particles, based on measured sieve size distributions given in Figs 8(a) and 8(b), are shown in Figs. 9(a) and 9(b), respectively (also by ∇). They are plotted as functions of the particle true size, using relationships (A.6) and (A.7) providing corrections for the sieve size, and illustrate results of the

modified sieving technique described in this paper. In following comparisons, these functions are called the "corrected sieve size distributions".

C. *A method for direct measurements of the true size distributions*

Another approach, not based on particle sieving, can be used for an independent measurement of the particle true size distribution. This approach is based on a grain-by-grain weighing of the largest particles in both carbonate (shell) and quartz (sand) particle populations. A threshold of 0.1 g was set as a minimal weight for shells, and 43 such particles were found in all ten cylindrical (BAMS and SAS) samples. The true size (equivalent diameter) of each particle was estimated from its weight using the known carbonate density. Then the particles were rearranged in the order of descending weight. Some particles had the same weight, within resolution of weight measurements (0.01 g), and to each weight in this descending series the number of particles having this weight was assigned. This number can be also understood as a number of particles in a weight resolution cell (or a bin for the corresponding weight). For the two series, weights and numbers, the two cumulative functions were calculated versus particle true size (defined by its weight).

This method was applied also to analysis of sand (quartz) particles, which were smaller and lighter. Only six particles were found to have weight not less than 0.05 g, the threshold set for sand grains. A lower threshold was not set because the limited resolution of the weighing scales did not allow a reasonably accurate segregation by weight for smaller particles. This method, therefore, has limitations related only with resolution of the available weight measurement method. The resulting series of weights (with corresponding true size) and numbers can be presented as a table, which provides a simple example for a data base (here for six quartz particles) used in this technique:

Weight, g	0.12	0.07	0.06	0.05
True size, mm	4.4	3.7	3.5	3.3
Number	1	1	1	3

Results for both carbonate and quartz particles are given in Figs. 9(a) and 9(b) (by circles) for volume- and number-size distribution cumulative functions. The comparison between these distributions, the directly measured "true size distributions" based on the non-sieving technique, and the "corrected sieve size distributions" based on a modified sieving technique (shown by ∇-symbols and discussed earlier), demonstrates a good fit and provides a test for the modified technique and empirically introduced corrections.

Generally, the method proposed here for direct measurements of the true size distributions seems to be practically useful for analysis of coarse particles, which are larger but less numerous, and for which there is no rationale for separating into size classes or bins. It can be used, for example, for rapid estimation of the size distribution of large particles in sediment grab samples, normally collected in oceanographic expeditions, bottom mapping surveys, etc. Large volumes of the sediment, usually delivered on-board in such grabs, can be pre-sieved to separate coarse particles, which can be quickly analyzed using this "express-method" requiring only simple weighing, from finer particles, which can be saved, if needed, and analyzed later in laboratory conditions using traditional techniques.

Therefore, this approach can provide complementary acoustics-related inputs to traditional sediment data bases, which are being commonly updated by data obtained during numerous sea trials and surveys. In particular, the results and techniques presented in this paper can be used for upgrades of sediment parameter data bases and empirical algorithms, such as described in [3,30]. Also, because this method provides direct measurement of true size distributions, it can be used as a testing tool for results obtained using traditional sieving and other non-direct measurement techniques.

VI. Summary and Conclusions

To provide inputs to acoustic scattering models, a more detailed description of the coarse tail of the sediment particle size distribution than it is commonly available is necessary. This also requires sediment samples having larger cross sectional areas and larger volumes, than commonly used for traditional analysis focused mainly on the central part of the size distributions. Also, a more accurate classification of the sediment type than is commonly available is required. In particular, from an acoustic viewpoint, the SAX04 environment can be more adequately characterized as a shelly sand/mud mixture, with spatially varying mud and shell components, because the small shell and mud contents in SAX04 sediment (commonly to be ignored) and their spatial distributions can be important inputs in models of bottom scattering and model/data comparisons.

In this paper, traditional weighing-sieving techniques were used with some modifications to provide corrections for the non-spherical shape of coarse particles. The SAX04 coarse particles can be described as a mixture of two populations, represented by carbonate (shells) and quartz (sand) particles, with different densities, as well as different shape and size distributions. The sieve-size distribution histograms and cumulative functions were determined for sieve sizes 1 mm and larger, at quarter-phi intervals. The size and shape distributions for both populations can be described by power laws, but with different power exponents. The

size distribution of quartz particles is much steeper than the size distribution of shells. This results in dominance of quartz particles over carbonate (shells) in the coarse sand size range, while shells are dominant in gravel and larger size ranges.

Shells and shell fragments are shown to have very different shapes than sand particles. To quantify the difference, a shape factor was introduced and determined. The measured shape factor was used also to determine the particle true size (equivalent diameter). For both populations, sand particles and shell fragments, the shape factor and true size, as functions of the particle sieve size, are shown to be well approximated by empirical power law dependences. These empirical relationships were used to provide corrections to measured sieve-size distributions and to determine the true-size distributions required in acoustic scattering models. These corrections are based on replacing the spherical shape assumption, used in traditional techniques, by the typical shape assumption using empirical relationships for the shape factor.

The true size cumulative distribution for a relatively small fraction of the largest particles was determined independently by means of a grain-by-grain analysis, not using traditional sieving techniques. The comparison with the true size distributions obtained by correction of the sieve-size distributions was used as a test for the proposed correction techniques. The true size distributions of coarse particles obtained in this paper will provide necessary input parameters for modeling of seafloor scattering. These inputs will be used in model/data comparisons and analysis of the SAX04 acoustic backscattering measurements. The results of this paper also can be used for upgrades of existing sediment parameter data bases and empirical algorithms.

APPENDIX A

EMPIRICAL RELATIONSHIPS FOR PARTICLE CHARACTERIZATION: POWER LAW APPROXIMATION

Several empirical relationships between parameters characterizing the particle shape and size distributions were presented in this paper. They all are approximated by power law expressions and summarized below. The volume ratio for the two populations, shell (carbonate) and sand (quartz) particles, R_v, and corresponding number-ratio, R_N, are of the form

$$R_v(d) = 0.06\, d^{4.5} \tag{A.1}$$

and

$$R_N(d) = 0.13\, d^{4.62}, \tag{A.2}$$

where the sieve size *d* is expressed in millimeters. Correspondingly, the R - parameter, the ratio of the shape factors of carbonate and quartz particles, F_c / F_q, also referred to as the “ratio of the ratios”, R_v / R_N, is of the form

$$R(d) = 0.45\, d^{-0.12}. \tag{A.3}$$

The shape factors themselves can be approximated by power laws as follows:

$$F_c(d) = 0.7\, d^{-0.45} \tag{A.4}$$

for carbonate particles, and

$$F_q(d) = 1.56\, d^{-0.33} \tag{A.5}$$

for quartz particles. They can be used to quantify a “typical shape” of particles in each population.

The equivalent diameters are found to be

$$D_c(d) = 0.89\, d^{0.85} \tag{A.6}$$

and

$$D_q(d) = 1.16\, d^{0.89} \tag{A.7}$$

for carbonate and quartz particles, respectively.

APPENDIX B

PHASE RELATIONSHIPS IN QUARTZ/CARBONATE MIXTURE

The average density in the quartz/carbonate mixture, ρ, and the volume ratio of the two components, R_v, are related as follows:

$$\rho = \frac{R_v \rho_c + \rho_q}{R_v + 1}, \quad R_v = \frac{\rho - \rho_q}{\rho_c - \rho}, \tag{B.1}$$

where ρ_q and ρ_q are the quartz and carbonate densities, respectively. The volume-size distributions of the carbonate and quartz

particle components, Ψ_{vc} and Ψ_{vq}, can be obtained from the total (non-segregated) volume-size distribution, Ψ_v, using any of the following relationships:

$$\Psi_{vc} = \frac{R_v}{R_v + 1}\Psi_v = \frac{\rho - \rho_q}{\rho_c - \rho_q}\Psi_v, \tag{B.2}$$

$$\Psi_{vq} = \frac{1}{R_v + 1}\Psi_v = \frac{\rho_c - \rho}{\rho_c - \rho_q}\Psi_v. \tag{B.3}$$

A similar description for number-size distributions in a mixture of two populations, carbonate and quartz particles, is based on the average shape factor F for the mixture, shape factors of the components, F_c and F_q, and the number ratio of the two populations, R_N, which are related as follows:

$$F = \frac{R_N F_c + F_q}{R_N + 1}, \quad R_N = \frac{F_q - F}{F - F_c}. \tag{B.4}$$

The number-size distributions of each component, Ψ_{Nc} and Ψ_{Nq}, can be obtained from the total (non-segregated) number-size distribution, Ψ_N, using any of the following relationships:

$$\Psi_{Nc} = \frac{R_N}{R_N + 1}\Psi_N = \frac{F_q - F}{F_q - F_c}\Psi_N, \tag{B.5}$$

$$\Psi_{Nq} = \frac{1}{R_N + 1}\Psi_N = \frac{F - F_c}{F_q - F_c}\Psi_N. \tag{B.6}$$

The volume and number ratios, R_v and R_N, and consequently average density and shape factor, ρ and F, appear to be spatially independent (at the SAX04 site). This can be important practically and provide alternative, less time consuming, ways for estimating the volume- and number-size distributions of the two components, carbonate and quartz particles, using the relationships given above. Indeed, one can see that it is sufficient to measure, e.g., the volume ratio only in one reference location. Then, assuming that this ratio is spatially independent in the area of interest, it is sufficient to measure the volume- or number-size distributions in other locations of this area without segregation of the two populations, to provide the required particle characterization for each population.

ACKNOWLEDGMENT

The author is grateful to Drs. M. Richardson and K. Briggs of NRL-SSC, and Dr. K. Williams of APL-UW, who arranged the sediment samples collection by NRL and APL divers, provided their data for comparisons, and also gave valuable comments on the first version of the paper. The author thanks Dr. D. Jackson of APL for helpful discussions and a careful first reading of the manuscript.

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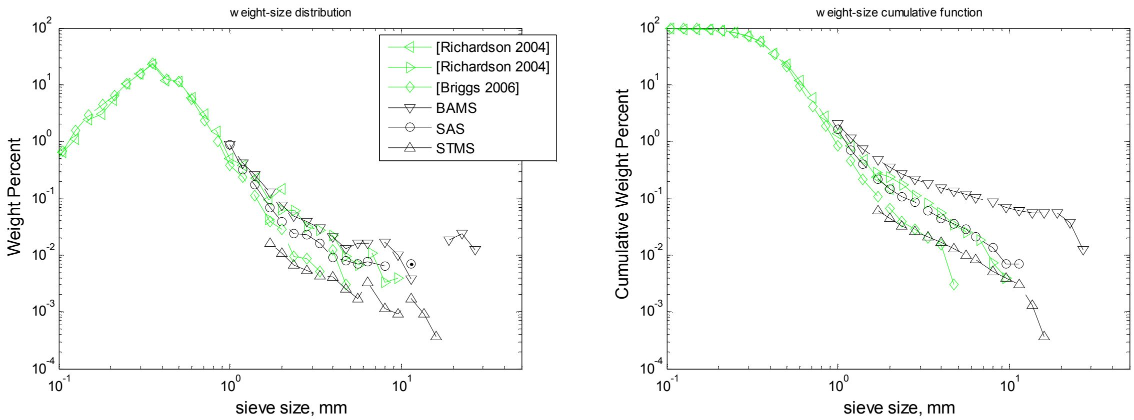
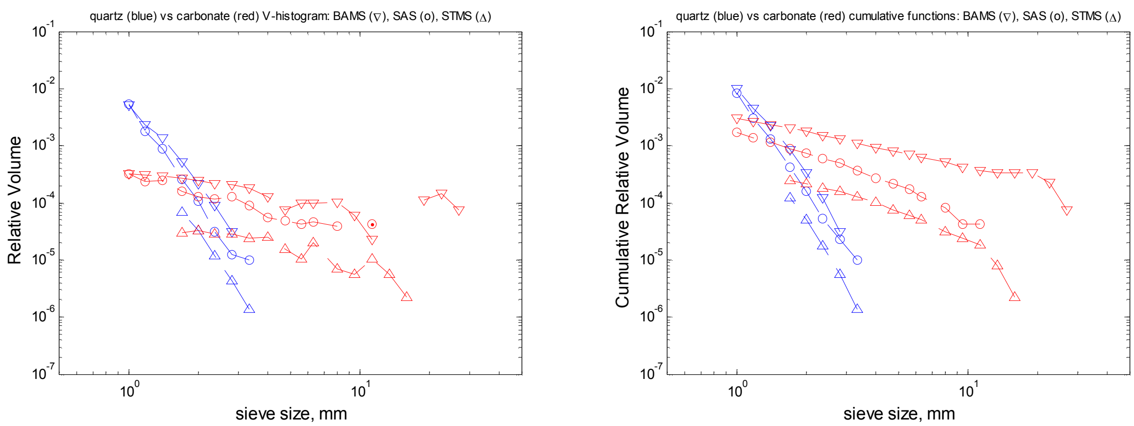


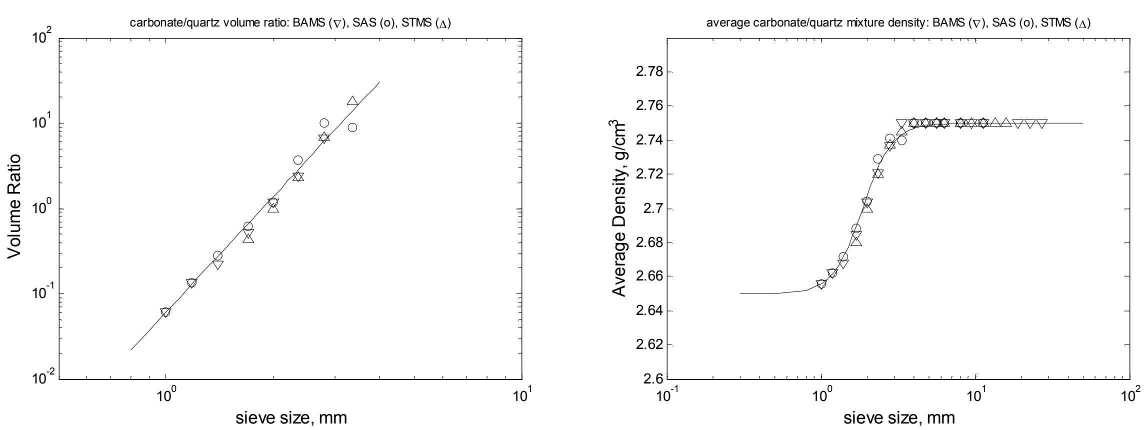
(a) (b)

Fig. 1. SAX04 grain size frequency distribution histograms (a) and cumulative functions (b): data obtained at BAMS, SAS, and STMS sites, shown in black (this work), and data by [Richardson 2004] and [Briggs 2006] shown in green.



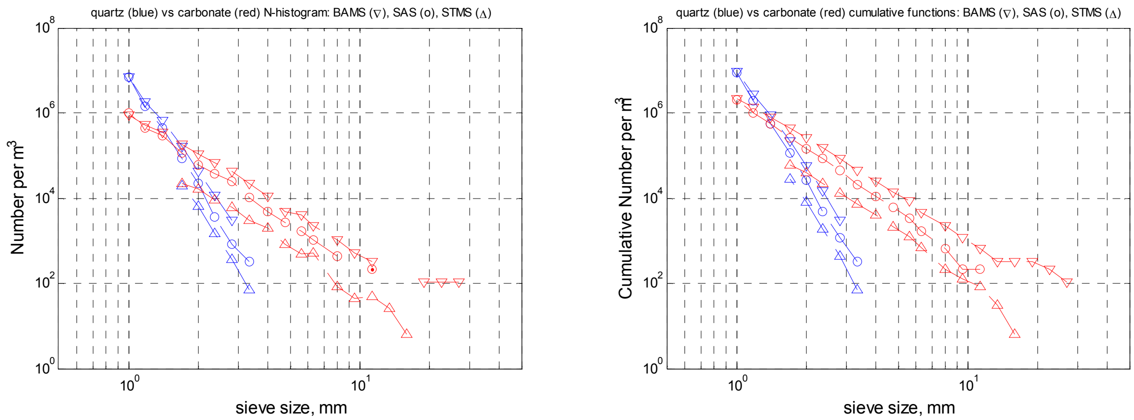
(a) (b)

Fig. 2. Volume-size distribution histograms (a) and cumulative functions (b) for sand (blue) and shell (red) particles. Symbols $\nabla, \mathrm{O}, \Delta$ correspond to BAMS, SAS, and STMS samples.



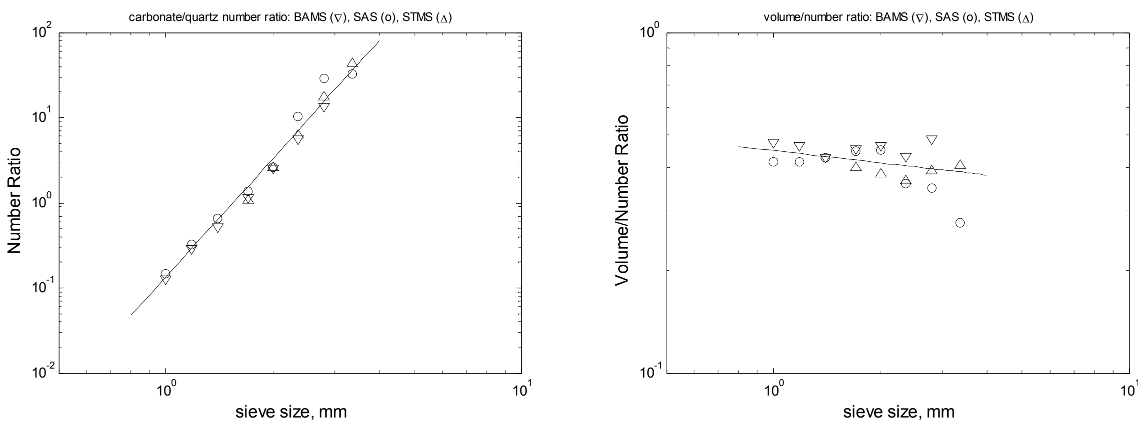
(a) (b)

Fig. 3. Volume-size distribution carbonate/quartz ratio (a), and average particle density (b). Symbols $\nabla, \mathrm{O}, \Delta$ correspond to BAMS, SAS, and STMS samples.



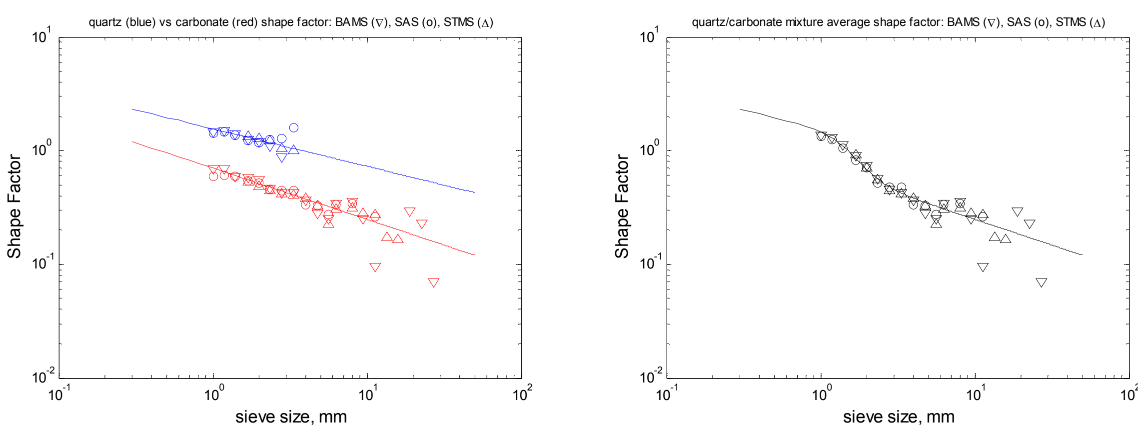
(a) (b)

Fig. 4. Number-size distribution histograms (a) and cumulative functions (b) for quartz (blue) and carbonate (red) particles. Symbols ∇, O, Δ correspond to BAMS, SAS, and STMS samples.



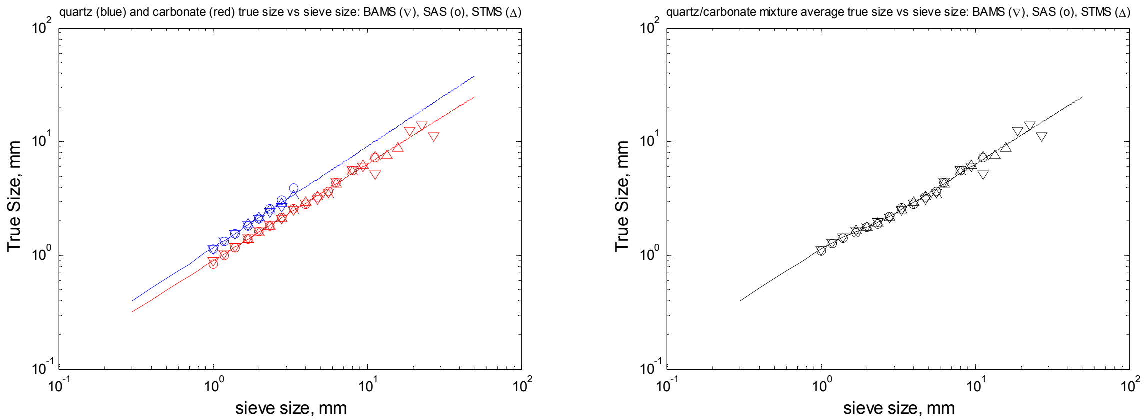
(a) (b)

Fig. 5. Number-size distribution carbonate/quartz ratio (a), and "ratio of ratios" parameter (b). Symbols ∇, O, Δ correspond to BAMS, SAS, and STMS samples. Solid lines show empirical power law approximations.



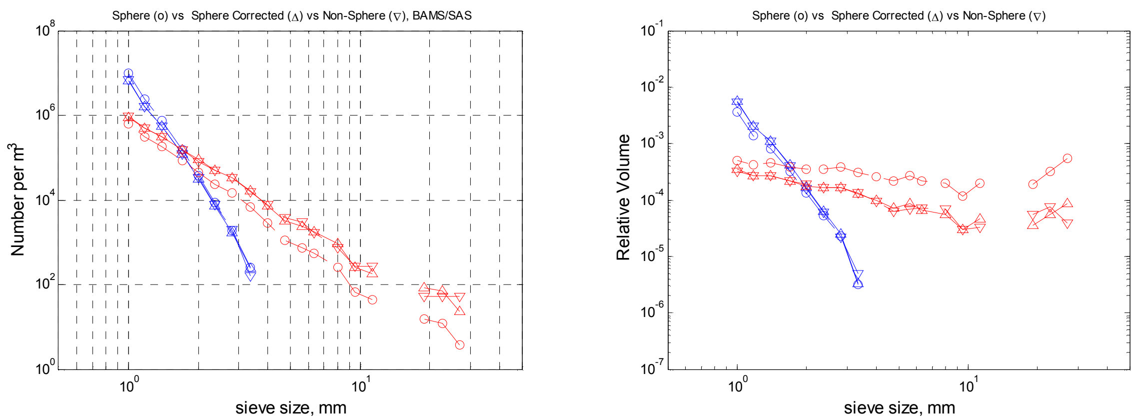
(a) (b)

Fig. 6. The shape factors of separated carbonate and quartz particles (a), and averaged for their mixture (b). Solid lines show empirical approximations. The shape factor equals to one for spherical particles. Data above this unit value correspond to elongated, e.g., egg-like particles (mostly quartz ones). Data below this unit value correspond to platy, e.g., disk-like, particles (mostly carbonate shells). Red, blue, and black symbols correspond to carbonate, quartz particles, and their mixture.



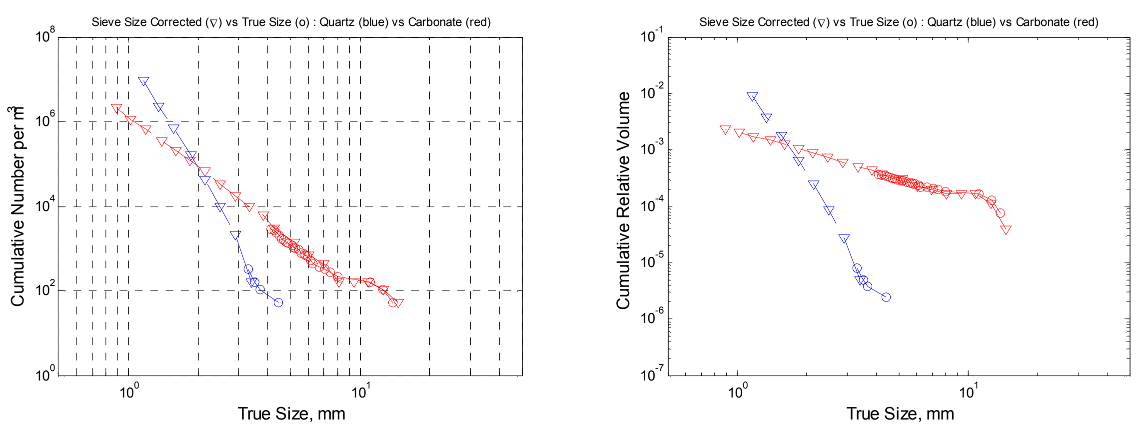
(a) (b)

Fig. 7. Relationships between the true size and the sieve size, shown for separated (a) particles, carbonate (red) and quartz (blue), and for non-separated (b), quartz/carbonate mixture (black). Solid lines show empirical approximations.



(a) (b)

Fig. 8. Measured number- (a) and volume- (b) size distribution histograms for ten BAMS/SAS samples (∇) in comparison with those obtained using “spherical shape” assumption without correction (circles) and corrected for the particle “typical shape” using empirical relationships (Δ). Red and blue symbols correspond to carbonate and quartz particles.



(a) (b)

Fig. 9. Cumulative number- (a) and volume- (b) “corrected sieve size distributions”, based on measured histograms (shown in Fig. 8) and plotted here (by ∇) as functions of the true size, compared with directly measured “true size distributions” (shown by circles). Red and blue symbols correspond to carbonate and quartz particles.

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
31-03-2009	Final Report	12 Sep 2006 - 31 December 2009

4. TITLE AND SUBTITLE Sediment Particle Characterization for Acoustic Applications: Coarse Content, Size and Shape Distributions in a Shelly Sand/Mud Environment	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** N00014-07-1-0172 **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Anatoliy N. Ivakin, University of Washington	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory University of Washington 1014 NE 40th St. Seattle, WA 98105	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Robert H. Headrick Office of Naval Research 875 N. Randolph Street Arlington, VA 22203-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Coarse particles in the sediment samples collected during the sediment acoustics experiment (SAX04) in shallow water off Fort Walton Beach, Florida, were analyzed in the 0 to –5 phi sieve size range, at quarter-phi intervals. Conventional size frequency histograms were determined and compared with results obtained by others at the SAX04 site. In addition, the coarse content was analyzed separately for the two populations, quartz (sand) and carbonate (shell) particles, using independent measurements of total weight and number of particles in each size interval. With this approach, four size distributions were measured, instead of a single one as in traditional sieving techniques. This analysis resulted in a modified technique, which can be used to improve geoacoustic characterization of the sediment. A particle shape factor was introduced for a simple quantification of the difference between the sieve size and true size (equivalent spherical particle diameter). It is shown that shells and shell fragments have a shape factor significantly different from that for sand particles. The size distributions for the two populations are also shown to be different. Empirical relationships are established between the shape factor, sieve size, and true size, for both carbonate and quartz particle populations. Using these relationships, the true size distributions, required in acoustic applications, were determined by correction of traditional sieve size distributions. These corrections are based on replacement of the “spherical shape” assumption used in traditional techniques by the “typical shape” assumption, using the shape factors measured for the two populations. Finally, to test the corrected distributions, they were compared with those obtained using a new approach allowing estimation of the true size distributions without particle sieving and/or separating into size intervals (bins). The true size distributions obtained in this work will provide input parameters and ground truth for model/data comparisons using SAX04 acoustic backscattering measurements.

15. SUBJECT TERMS

Coarse sand, gravel, shell fragments, sieve size, true size (equivalent diameter), particle size and shape distributions.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	U	15	Anatoliy N. Ivakin **19b. TELEPHONE NUMBER** *(Include area code)* (206) 616-4808

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